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Neutral gas temperatures in a multipolar electron cyclotron resonance plasma

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Optical emission measurements of the Doppler broadening of argon (549.6 nm) and helium (501.6 nm) neutral lines in the unmagnetized regions of an electron cyclotron resonance plasma show that the gas temperature ranges from 300 to 900 K. After compensation for Zeeman splitting, Doppler widths are found to be constant across the radius of the plasma. Plasma heating of the argon gas (0.77 mTorr) is shown to increase from 300 to 500 K as microwave power absorption increases from 80 to 330 W. Long neutral residence times are observed to increase the argon gas temperature to $\approx$900 K. Helium and argon neutral temperatures decrease as the neutral mean free path increases indicating that the gas may be heated by ion-neutral collisions including charge exchange.

As electron cyclotron resonance (ECR) plasmas gain acceptance with the plasma processing industry, it is important that the plasma physics within these devices be better understood. Ions and electrons typically have energies on the order of 0.1–20 eV in ECR plasmas[1–4] due to interactions with strong electric and magnetic fields. Neutrals in the plasma may then gain considerable kinetic energy from elastic collisions or charge exchange with these more energetic charged particles. Although ECR plasma processes such as dry etching are often "ion assisted" in nature, neutrals and free radicals in the discharge also contribute to plasma-surface interactions (e. g., spontaneous etching of trench sidewalls). In addition, neutral heating may ultimately limit the ion density attainable in a plasma due to rarefaction of the source gas. In a preliminary effort to quantify the role of neutral and free radical energies in multipolar-ECR plasma processing, we have determined the temperature of argon and helium neutrals by measuring optical emission line profiles as a function of microwave power absorption, gas pressure, and mass flow rate.

The ECR plasma source used in this work is shown schematically in Fig. 1, and described in detail elsewhere.[4–6] Microwave radiation (2.45 GHz) is introduced into a variable length resonant cavity which focuses the microwaves in a 12.5 cm i.d. quartz discharge chamber. The ECR magnetic field is produced by an octapole array of Nd-Fe-B magnets which surround the discharge. The B field radially decreases from >1000 G at the inside wall of the chamber to <50 G in the center and passes through the ECR field strength of 875 G at ≈ 1 cm from the chamber wall. Since there is no axial B field like that in *divergent-field* ECR sources,[1–3] the plasma diffuses into the processing chamber rather than streaming.

Emission, primarily from the active discharge region of the plasma, was collected by an optical fiber bundle with an acceptance cone of 15° (see Fig. 1). The light emerging from the opposite end of the fiber was collimated and passed through a Fabry–Perot interferometer, a monochromator, and detected by a cooled photomultiplier tube (PMT). The instrumental broadening of this optical sys-

from the unmagnetized volume of a 150 W, 0.67 mTorr, 10 sccm xenon ECR discharge. After deconvolution of the $(7\pm1)\times10^{-4}$ nm Doppler width $(600\pm150$ K) of the xenon line, the instrument response was found to be Gaussian with a full width at half maximum (FWHM) resolution of $(\Delta\lambda/\lambda) = (3.5\pm0.1)\times10^{-6}$. This corresponds to a spectral resolution of $(1.92\pm0.06)\times10^{-3}$ nm for the 549.6 nm Ar line and $(1.76\pm0.05)\times10^{-3}$ nm for the 501.6 nm He line. All subsequently measured line profiles were deconvolved from the instrument response. Detail in the argon spectral line shapes was obscured by instrument broadening. Helium lines, however, were considerably wider than the instrument resolution (typically 0.0045 nm) and appeared to be symmetric and Gaussian in shape.

The emission line profiles observed in plasmas may be broadened by many factors. Natural and collisional broadening are insignificant[1] compared to the Doppler width (FWHM) which is given by

$$\Delta\lambda_D = 7.16\times10^{-7}\lambda_0[T/M]^{1/2},$$

where T is in Kelvin and M is the mass of the emitting species in amu. Typical charged particle densities in this discharge are on the order of $10^{11}/\mathrm{cm}^3$ which is roughly two orders of magnitude less than densities which produce significant Stark broadening.[8] Stark broadening due to the microwave fields in the plasma [$\sim$7 kV/m at 250 W (Ref. 9)] is estimated to be on the order of 10^{-5} nm. It is not possible, however, to neglect Zeeman splitting of lines in an

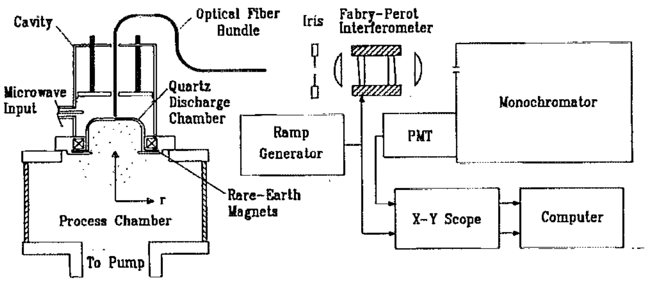

FIG. 1. Schematic view of the microwave plasma disk reactor (MPDR)

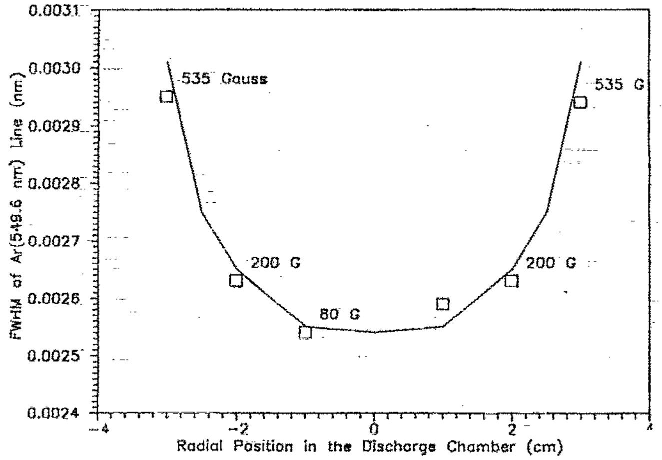

FIG. 2. Comparison of measured line widths and Zeeman effect imply a uniform temperature distribution in the radial direction. Note the measured peak magnetic field strengths are listed next to each data point.

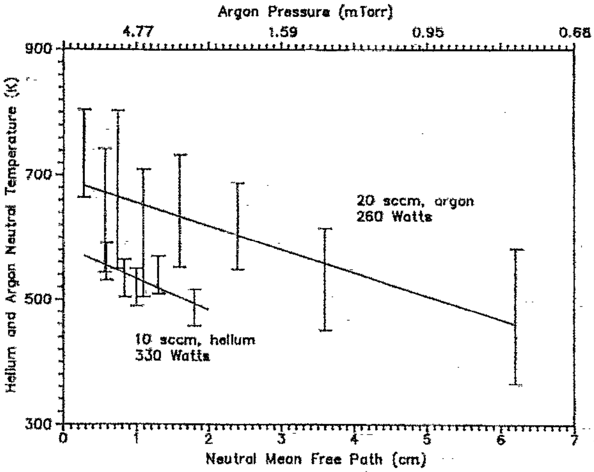

FIG. 4. Variation of helium and argon neutral temperature with neutral mean free path. Note that the upper axis applies to argon only (the helium pressure ranges from 7.5 to 23 mTorr).

ECR discharge due to the strong static magnetic fields (875 G). The measured 549.6 nm line widths in a 20 sccm, 0.77 mTorr argon discharge are plotted as a function of radial position (and *B* field) in the plasma in Fig. 2. Assuming a constant Doppler profile of 0.002 nm (i.e., a constant temperature), the solid curve represents the computed Zeeman broadening[8,10] after convolution with the instrument response. The close agreement between experiment and calculation implies that the temperature is uniform across the discharge as expected when the mean free path is of the order of the plasma chamber characteristic length. Subsequent data were measured along the vertical axis in the central volume ($r=0$) of the discharge chamber where the Zeeman splitting is negligible.

The argon ($\lambda = 549.6$ nm) neutral temperature at low input power (<100 W) is nearly room temperature as shown in Fig. 3. Increasing the absorbed power in an ECR discharge increases not only the ion density,[9] but also the neutral gas temperature. This suggests that energetic neutral particles are produced by collisions with charged particles, charge exchange with ions, or generated by electron-ion wall recombinations. (Electrons in the plasma are heated by electron cyclotron resonance and ions are accelerated by ∇B forces and/or plasma potential gradients.) Extrapolation of these data indicates that the neutral temperature may exceed 1000 K for absorbed powers of 1–2 kW as previously reported by differential pressure measurements.[11] The error bars were determined by repeated temperature measurements. The uncertainty in the temperature measurement is dominated by background noise rather than instrument resolution calibration.

Gas temperatures as a function of process chamber pressure for a constant absorbed power and mass flow rate are presented in Fig. 4. When plotted as a function of neutral mean free path (mfp), the temperatures are observed to decrease nearly linearly with mfp, thus supporting the model that the neutrals are collisionally heated. Under conditions of long mfp the neutrals are also in better contact with the chamber walls and are therefore cooled more effectively. Finally, note that helium neutrals (λ_0

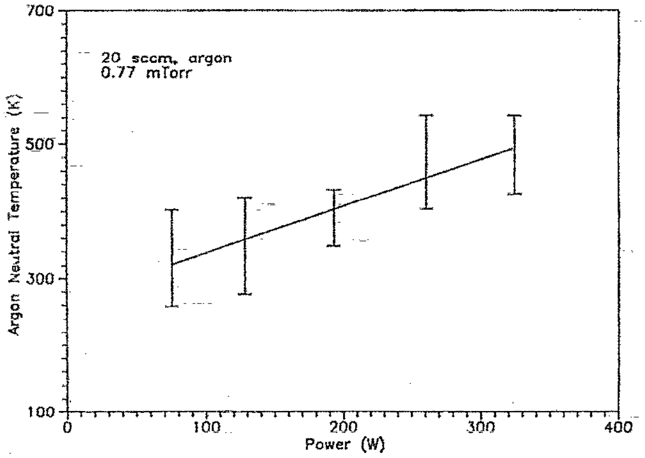

FIG. 3. Argon neutral temperature measured along the central axis of the

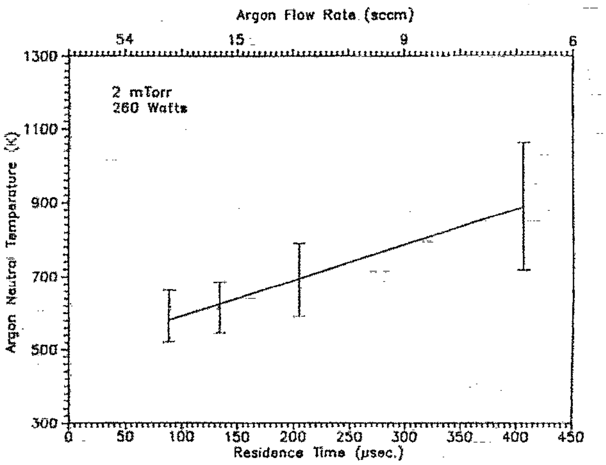

FIG. 5. Argon neutral temperature variation as a function of gas resi-

= 501.6 nm) are considerably less energetic than argon neutrals due, at least in part, to higher neutral gas thermal conductivity and lower ion densities in helium.

The effect of residence time on argon neutral temperature was measured by varying the flow rate at a constant pressure of 2 mTorr (see Fig. 5). The rapid increase in gas temperature observed for long residence time plasmas indicates that as flow rate increases a significant portion of the neutral gas energy is transported downstream from the ECR heating zones. These data also show that variation of pumping speeds and flow rates can be used to control plasma temperatures, perhaps most critically under high-power absorption conditions.

Additional research is planned to further elucidate plasma heating and cooling mechanisms, including the effect of plasma chamber and substrate temperature control. Free radical and ion temperatures in reactive process gases using absorbed powers up to 3 kW in both larger and smaller discharge geometries should also add insight into neutral gas heating mechanisms.

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